GUIDANCE FOR THE USE OF GEOSYNTHETIC CLAY LINERS (GCLs) AT SOLID WASTE FACILITIES

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NOTICE: This document is intended solely as guidance, and does not contain any mandatory requirements except where requirements found in statute or administrative rule are referenced. This guidance does not establish or affect legal rights or obligations and is not finally determinative of any of the issues addressed. This guidance does not create any rights enforceable by any party in litigation with the State of Wisconsin or the Department of Natural Resources. Any regulatory decisions made by the Department of Natural Resources in any matter addressed by this guidance will be made by applying the governing statutes and administrative rules to the relevant facts.

I. INTRODUCTION

A. Purpose of Guidance

Geosynthetic clay liners (GCLs) are increasingly being used as an alternative to compacted clay in landfill liner or cover systems at waste management facilities nationwide. In the past few years, Wisconsin DNR staff have encountered a number of proposals to substitute GCLs for the liner-quality clay specified in s. NR 504.06, Wis. Adm. Code, and as upgrades to previously approved soil caps and liners that do not meet current standards. This document is intended as a resource for department waste management personnel involved in permitting, inspecting and approving the installation of GCLs at solid waste facilities in Wisconsin.

The guidance is divided into five parts. The remainder of this introduction provides a general description of current GCL technology and outlines some of the advantages and concerns associated with GCLs in solid waste applications. Chapter II describes the GCL solid waste uses that are most applicable to Wisconsin. Chapters III and IV present design and construction/documentation guidelines, respectively, for GCL waste management applications in Wisconsin. Chapter V provides a selective bibliography of GCL-related references from the scientific, engineering and trade literature.

This guidance document was prepared by a team of DNR staff members consisting of Robert Grefe, Ann Bekta, Sue Fisher and Brad Wolbert. Questions about the guidance can be directed to any one of these individuals or to the chief of the Technical Support Section in the Bureau of Waste Management.

B. Description of GCL Technology

ASTM D 4439, "Terminology for Geosynthetics," defines GCLs as "**...factory manufactured hydraulic barriers typically consisting of bentonite clay or other very low permeability materials, supported by geotextiles and/or geomembranes, which are held together by needling, stitching, or chemical adhesives.**" Examples of currently available products are outlined in Table 1. These can be divided into two types: (1) a "sandwich" construction consisting of a thin (about 1/4-inch) layer of sodium bentonite between two geotextiles, and (2) a two-layer construction comprised of a thin (1/4-inch) mixture of sodium bentonite and adhesive glued to a geomembrane. Several variations on these two types of construction are available: the geotextiles in the sandwich construction may be woven or needlepunched; the materials may be glued, stitched or needlepunched together; the bentonite in the sandwich construction may also be mixed with an adhesive for extra stability or with an additive to increase chemical resistance; and the geomembrane component of the two-layer construction may vary in thickness from 20 to 100 mils and may be textured on one or both sides for additional friction on slope applications. Custom-designed products are also available.

GCLs were first manufactured in the early 1980's and were originally used in exterior waterproofing of building foundations. They were first applied to landfill liner technology in 1986. They are manufactured in large rectangular panels having widths of 13 to 17 feet and lengths of 75 to 200 feet. Typically they contain 0.75 pounds of sodium bentonite per square foot in the dry state (corresponding to about 1 pound per square foot in the as-delivered state of 6 to 20 percent moisture content), and are delivered in rolls weighing from 1,400 to 4,000 pounds.

A GCL creates a hydraulic barrier when the bentonite component is hydrated with water. As it absorbs water molecules into its mineral structure, dry, unconfined sodium bentonite swells in volume by a factor of approximately 15 and experiences a consequent decrease in hydraulic conductivity. Sodium bentonite that is fully hydrated with clean water has a hydraulic conductivity of 1×10^{-8} to 1×10^{-10} cm/sec, depending on the confining stress (compression of the bentonite lowers the hydraulic conductivity).

C. <u>Advantages of GCLs</u>

Research and experience have shown that GCLs offer a number of advantages over traditional compacted clay components of landfill liner and cover systems:

- Availability: GCLs can be shipped anywhere; liner-quality clay is subject to local availability and involves much greater volumes of material.

- Ease of Construction: GCLs can be deployed relatively rapidly in the field, reducing the effects of adverse weather on construction quality, so long as they are not allowed to prematurely hydrate by contact with rain. Quality assurance and control procedures are somewhat simpler with a GCL than with compacted clay. Also, extensive heavy equipment fleets are not needed to install a GCL. Installation of a GCL results in less fuel consumption and air and noise pollution.

- Resistance to Differential Settling: The barrier created by a GCL may be slightly less affected by differential settling (i.e., in a cover application) than compacted clay, due to the higher overall tensile strength of GCLs compared to compacted clay soils. GCLs are also easier to repair.

- Uniformity: The engineering properties of GCLs are consistent and uniform within the manufacturer's specifications, reducing variations in performance from point to point in a properly constructed barrier and eliminating some of the construction variables associated with compacted clay.

- Cost: Material costs for a GCL may be less than the purchase cost of clay, if the clay hauling distance exceeds a few miles. Moreover, installation of a GCL generally costs significantly less than installation of compacted clay, when all time and materials costs are considered.

- Preliminary Field Performance: Data on leakage rates into the leak detection layers of double-lined systems have shown significantly lower leakage for geomembrane/GCL composite liners compared to (generally 2-foot-thick) geomembrane/clay liners. At least in the short term, the field data indicate that geomembrane/GCL liners are as effective as, and may be more effective than, geomembrane/clay liners in terms of leakage rate.

D. <u>Concerns</u>

There are several concerns associated with the use of GCLs in landfill liner and cover systems:

- Chemical Resistance: GCLs do not have the natural diffusion and adsorption capacity of several feet of compacted clay in liner applications. Moreover, multivalent cations in leachate, such as calcium and magnesium, can replace sodium ions in the bentonite structure, reducing the tendency of the bentonite to swell and increasing the hydraulic conductivity. Other leachate constituents that may increase hydraulic conductivity include concentrated organic liquids and petroleum hydrocarbons, concentrated electrolytic solutions, and strong acids and bases. This phenomenon can also occur in cap applications where overlying soil materials are high in calcium or magnesium.

  In the case of liners, suspended solids, microorganisms, and precipitates might partially offset these ion exchange effects by clogging pores and voids. Final cover systems, however, may be more vulnerable to impaired performance due to the combined effects of desiccation cracking, inadequate overburden stress, and loss of plasticity caused by multivalent ions from the cover soils replacing sodium in the clay structure.

  Use of a GCL in a final cover design may always require a covering geomembrane, pond liner, or plastic sheeting to protect the bentonite in the GCL from desiccating. Recent research has described field and laboratory demonstrations where GCLs installed without a covering geomembrane developed a cracking pattern and allowed high infiltration rates. Apparently, percolating water mobilizes multivalent cations in cover soils, which upon contact with the GCL reduce the plasticity of the GCL's bentonite layer. Infiltration is also increased by the desiccating effects of dry weather and plant transpiration.

- Physical Strength: Hydrated sodium bentonite has relatively low internal shear strength. Needle punching and stitching increase the internal shear strength of GCLs, but the use of GCLs on slopes requires careful design and may be subject to more conservative limits than compacted clay. Engineers and contractors have less experience with GCLs than with compacted clay. GCLs also have little tensile strength at overlapped panel seams, where mechanical bonding is absent. The long-term effects of downslope creep on GCLs--e.g., the potential for pull-out of the reinforcing fibers under continuous long-term application of shear stress--are unknown.

- Permeability to Air and Landfill Gas When Dry: Bentonite is an ineffective barrier to gas migration unless it is kept adequately hydrated (GCLs containing a geomembrane component, or GCLs used in conjunction with a geomembrane, avoid this problem).

- Puncture Resistance and Thinning: The bentonite component of GCLs is capable of self-healing small (less than 1-inch diameter) punctures, but larger punctures or penetrations where foreign material fills the hole can increase leak rates. Foreign objects can puncture the thin GCL layer more easily than a several-foot-thick layer of compacted clay. Thinning of the bentonite in the GCL can occur where rocks protrude from the subgrade or an overlying soil layer; where an overlying geomembrane is wrinkled; or where insufficient cover soil is placed over the GCL for traffic protection, compromising the GCL's resistance to water movement at those points.

- Free Swell: If adequate confining pressure is not applied to the GCL immediately after installation, free swell of the bentonite will occur as the GCL adsorbs water from the soil subgrade or from precipitation. If this bentonite is subsequently allowed to dry, voids and cracks may form. These spaces may not completely close upon rehydration, or may fill with soil instead of bentonite.

- Intimate Contact: In a conventional composite liner, a geotextile would not be allowed between a geomembrane and the compacted clay layer, due to the potential for flow to occur along the plane of the geotextile. The thickness of the geotextile and the compressive stress appear to be critical factors in determining the geotextile's transmissivity. Acceptable intimate contact between the GCL and the geomembrane can be achieved if the GCL includes a relatively lightweight (6 to 8 ounces per square yard) geotextile in contact with the geomembrane.

- Contaminant Breakthrough Time: A continuously flooded GCL may allow liquid discharge from its base in a few weeks, while a continuously flooded compacted clay layer may resist breakthrough for years.

- Brief Historical Record: GCLs have a relatively short performance track record; research into their capabilities and limitations is still being conducted. In addition, engineers and contractors are not as experienced with GCLs as with compacted clay, and quality assurance observation and testing methods are not as routine.

TABLE 1: EXAMPLES OF COMMERCIAL GCL PRODUCTS AVAILABLE IN 1997

Product Name	**Manufacturer**	**Rein-forced?**	**Description**
Bentofix NS	Albarrie-Naue, Ltd. (Nat'l Seal Co.)	Yes	Bentonite layer sandwiched between a woven geotextile (top) and a nonwoven geotextile (bottom); the textiles are needle-punched together through the bentonite
Bentomat CL	CETCO	Yes	Same as Bentofix but with a thin flexible membrane liner laminated to the outside of the nonwoven geotextile
Bentomat DN	CETCO	Yes	Bentonite layer sandwiched between two non-woven geotextiles; the textiles are needle-punched together through the bentonite
Bentomat SS	CETCO	Yes	Same as Bentofix, but with contaminant resistant bentonite
Bentomat ST	CETCO	Yes	Same as Bentofix
Claymax 200R	CETCO	No	Bentonite/adhesive layer sandwiched between two lightweight woven geotextiles
Claymax 600CL	CETCO	No	Same as Claymax 200R but with a thin flexible membrane liner laminated to the outside of one of the geotextiles
Claymax 600SP	CETCO	Yes	Bentonite/adhesive layer sandwiched between two woven geotextiles which are stitched together to increase internal shear strength
Gundseal	GSE Lining Technologies, Inc.	N/A	Bentonite/adhesive layer (top) attached to a polyethylene (high-density or very low density), textured or non-textured geomembrane; contaminant-resistant bentonite also available

II. POTENTIAL APPLICATIONS OF GCLs TO SOLID WASTE FACILITIES

Section NR 500.08(4), Wis. Adm. Code, allows for alternative designs, materials, construction methods, documentation methods or testing methods at solid waste facilities. The project proponent must demonstrate that the alternative will provide for satisfactory solid waste handling or disposal at least as protective as the standard method or design described in the code.

This chapter outlines potential GCL uses that are most applicable to solid waste facilities in Wisconsin. GCLs should be used in conjunction with geomembranes when intended as a substitute for some thickness of natural clay, and, in addition, should be underlain by an additional low-permeability soil barrier layer as a combination subgrade for and backup to the GCL. Because the properties of clay and leachate, styles of GCLs, and site conditions vary greatly, this guidance makes no attempt to specify a standard thickness of clay that can be replaced by a GCL.

A. Liner Applications

Experience has shown, and laboratory testing has confirmed, that typical municipal landfill leachate generally presents little threat to the integrity of thick compacted clay liners. However, GCLs are much thinner and offer much less mass to resist alteration by leachate and subsequent contaminant penetration. Moreover, the sodium bentonite in GCLs is far more chemically sensitive than the clay minerals typically found in Wisconsin clays, and thus is more susceptible to chemical attack. For proposed liner applications, therefore, the GCL's ability to resist chemical degradation should be tested using full-strength leachate generated by the waste and taking leachable constituents from overlying soil and waste layers into account. If geochemical compatibility between the leachate and the GCL cannot be demonstrated satisfactorily through testing, then compacted natural clay should be used in the liner.

GCLs should also be tested for physical compatibility with the other liner components. Physical compatibility testing should address slope stability, usually through direct shear testing; tests should include hydration of the GCL and wetting of other geosynthetic and soil surfaces, and the tests should be run long enough to determine both peak and large-displacement shear strength values.

For further assurance of liner integrity as constructed, composite liner designs using GCLs should also incorporate electrical resistivity testing of the geomembrane component. This will reduce the frequency of holes in completed geomembrane installations and also reduce the consequences of leachate impacts on the GCL component of the liner.

1. Municipal solid waste landfills

GCLs should not be proposed as an appropriate replacement for the 4 feet of clay required by NR 504.06 for municipal solid waste landfills. Municipal landfill leachate is a complex mixture of organic and inorganic compounds whose individual concentrations vary considerably and unpredictably. Such leachate is better contained by a thick layer of natural clay than by GCLs, whose bentonite component can be affected by high salts concentrations as well as by high concentrations of divalent ions. Well-compacted clay liners tested with leachate in permeability test setups have shown good performance, and are not expected to change behavior significantly due to permeation with leachate. The field performance of compacted clay liners in Wisconsin has supported this expectation. The long-term performance stability of GCLs is less certain. In addition, a thick natural clay layer appears more likely to retard the movement of volatile organic compounds than a GCL over the long term.

2. Industrial solid waste landfills

GCLs have the potential to be used for these facilities as part of a composite liner, in conjunction with an overlying geomembrane component and an underlying soil barrier layer, if chemical compatibility with the leachate can be established. A composite cap should also be proposed for a site utilizing a composite liner.

3. Demolition waste landfills

For those demolition waste landfills that are required to be lined, a geomembrane, GCL and underlying soil barrier layer may be appropriate. Chemical compatibility problems arising from the prevalence of high-calcium materials in demolition wastes may be managed through a waste screening program that excludes high-calcium wastes.

4. Other facilities

Where the following other types of solid waste facilities are required to be lined, the liner design could include a GCL (in conjunction with a soil barrier layer and a geomembrane) provided the waste is not likely to adversely affect the behavior of the bentonite in the GCL. The liner design should be based on the potential groundwater impact from the waste and the potential effects of leachate on the GCL.

- Storage, transfer, processing, and stockpile sites: These facilities should be designed to protect the liner from traffic rutting and differential loadings, as well as the effects of freezing and desiccation, which generally means layers of drains, cover soils, and surface courses. The liners for these facilities are typically not protected by thick layers of overlying wastes as are landfill liners.

- Dredged material and other special waste disposal sites: These are generally regulated under a grant of exemption process. For a disposal site to be considered for an exemption, the waste types should be low in leaching potential and potential groundwater impact compared to municipal and industrial solid wastes. This does not preclude requiring leachate collection, if appropriate.

- Non-MSW landfills with old approvals for outdated liner design or materials: A GCL, soil barrier, and a geomembrane may be an appropriate liner design for sites that were originally approved with what would currently be considered substandard liner design or materials. Factors to be considered in such a decision would include the size of the facility, waste type, leachate volumes and quality, groundwater history and impacts, and remaining site life. A corresponding upgrade of the final cover system would generally be necessary where the liner is being upgraded.

B. Final Cover Applications

For proposed final cover system applications, GCLs should be tested for physical compatibility with the other cover components in a manner similar to that described previously for liner systems. Chemical compatibility with leachate is usually not an issue with final cover systems, except for landfills containing compressible, low-permeability waste masses such as industrial and municipal sludges. However, chemical compatibility with the water percolating through cover soils atop a GCL may be a problem, especially if desiccation of the GCL occurs.

A one-foot sand drain layer or geosynthetic equivalent above the capping layer (i.e., the GCL/soil barrier layer, which may also include a geomembrane) should be included in the final cover design for any site with slopes that exceed 10%.

Landfills for papermill sludges and other low-strength wastes usually impose additional constraints involving support of vehicles during construction, and settlement during and after construction. It may not be possible to transport and place compacted clay or a soil barrier layer on low strength waste masses. GCLs may be necessary to address the requirements of NR 504.07 for weak subgrade wastes. Where the waste mass will not support construction efforts or assure the long-term integrity of a soil barrier layer, final cover design may result in a capping layer that includes a GCL and geomembrane but without the soil barrier layer. The GCL then provides the only backup for the geomembrane. To assure that the GCL is not compromised by contact with leachate or gas, or by settlement, the design should include a drain layer below the capping layer as well as a reinforcing and support layer made of geotextile or geogrid and sand, bark, ash, and other fill materials. Additional geotextiles may be needed to separate the drain and support layers.

1. Composite capped landfills

Municipal solid waste landfills: A soil barrier layer and GCL combination may provide an appropriate substitute for the 2-foot clay component of the typical composite final cover. The requirements for a geomembrane as part of the final cover system should not be altered. The soil barrier should be two feet thick, or the same thickness as the compacted clay layer that it replaces. The upper foot of the soil barrier should be fine-grained, and compacted to a high density and at a moisture content near optimum. The lower foot of soil could be partially or wholly replaced with a dense, granular industrial waste such as well-compacted combustion ash or foundry sand, provided this volume is accounted for as part of the site's licensed waste capacity. The lower foot of soil barrier material would not be in direct contact with the GCL and could potentially meet less rigorous specifications for inclusion of gravel and stones.

Industrial solid waste landfills: A soil barrier layer and GCL combination may provide an appropriate substitute for the 2-foot clay component of the typical composite final cover. The requirements for a geomembrane as part of the final cover system should not be altered. The soil barrier should be one to two feet thick. The upper foot of the soil barrier should be fine-grained, and compacted to a high density and at a moisture content near optimum. The lower foot of soil could be partially or wholly replaced with a dense, granular material such as well compacted combustion ash or foundry sand provided this volume is accounted for as part of the site's licensed waste capacity. The lower foot of soil barrier material would not be in direct contact with the GCL and could potentially meet less rigorous specifications for inclusion of gravel and stones.

2. Clay-capped landfills

The approved designs of most municipal solid waste landfills approved prior to the mid-1980s, and of most industrial solid waste landfills, include a capping layer of 2 feet of compacted clay that generally meets clay liner specifications.

Clay-lined phases of municipal solid waste landfills: For active landfills and closed landfills larger than 50,000 cubic yards, a clay-lined phase could potentially be capped with a soil barrier layer, GCL, and geomembrane.

Industrial solid waste landfills: For foundry wastes, ash, and other industrial solid wastes with good bearing capacities, the clay capping layer can potentially be replaced with a soil barrier layer, GCL, and geomembrane. Closed landfills could propose to use a soil barrier layer and GCL, if the purpose is to replace a soil capping layer that does not meet clay liner specifications.

Landfills for papermill sludges and other low strength wastes may have to be designed with low topslopes and minimal sideslopes. In these cases, a drain layer may be needed and could consist of a geocomposite drain, 1 foot of sand, or a network of flexible, corrugated polyethylene piping placed over the capping layer.

Demolition waste landfills: For intermediate sized (50,000 to 250,000 cubic yards) demolition waste landfills, which are required to be lined and capped with compacted clay, the capping layer could potentially be replaced with a soil barrier layer, GCL, and a geomembrane.

C. Other Applications

Patching: GCLs are useful as patches, pads, or fillers around penetrations of the final cover, such as gas wells, headwells, and control valves. Where used, GCLs do not replace natural clay, geomembrane, or other capping elements, but are used to assure a low potential of infiltration in areas that are difficult to construct, to assure integrity of the cap, and to test properly.

Secondary containment: A GCL may be appropriate for wrapping pipes or manholes outside the limits of fill of the landfill, as long as the piping is subject to regular pressure testing. The backfill around pipes and manholes should be of soil barrier quality as described in this guidance.

Pond and lagoon construction: A combination soil barrier layer, GCL and geomembrane has potential for lining ponds and lagoons.

Building on abandoned landfills: Where a capping layer is required as a condition of building a structure on an abandoned landfill, a GCL with a geomembrane and soil barrier layer could potentially be used as long as sufficient supporting soil is placed below the capping layer and a minimum overall thickness of three feet of cover soil, topsoil and drain are placed above the capping layer. Where control of decomposition gas is required, the design may have to be upgraded to a composite capping layer or replaced with a minimum of two feet of compacted clay. In such cases, a gas venting layer and vent piping should be part of the design.

Beneficial use projects under ch. NR 538, Wis. Adm. Code: Beneficial use projects can include a wide variety of activities and materials. Locations that might include use of a GCL are storage or processing areas and capping layers for permanent use locations, for those projects where the leachability of the waste could affect groundwater or surface water.

Use of a GCL as a liner under a processing or storage facility requires evaluating leachate effects, desiccation effects, and traffic effects. The leachability of the waste and protective aggregate should be evaluated for effects on the behavior of the GCL. A covering layer of sand and gravel layers should be thick enough to distribute the weight of vehicles and stockpiles and prevent puncturing or lateral displacement of the bentonite. A soil barrier layer should support the GCL, and it may be necessary and practical to cover the GCL with fine to medium sand rather than gravel as a drainage medium. The GCL itself should be covered with a geomembrane or plastic construction sheeting to limit loss of water by the bentonite in the GCL and subsequent desiccation cracking.

As part of a cover structure over waste in a beneficial use project, a clay capping layer could potentially be replaced with a soil barrier layer and GCL, if the purpose is to replace natural clay with substandard qualities compared to clay liner specifications. The capping layer should be protected by a three-foot thickness of rooting zone and topsoil. If there is any potential for gas generation in the waste, a gas venting layer or system should be incorporated into the design.

III. DESIGN GUIDELINES

The development of GCLs has been recent enough that the practices associated with good design and installation are still evolving. The following guidelines are based on recommendations that department staff have been able to obtain from outside sources, as well as experience from projects approved to date. They are subject to change as new information becomes available.

A. Chemical Resistance

Sodium bentonite is susceptible to major changes in its permeability if leaching fluids contain either high inorganic salt concentrations or high concentrations of divalent ions (e.g., calcium, magnesium, iron and other metallic elements). Hydrated GCLs have been shown to increase in permeability by 5 or 6 orders of magnitude after contact with some strong leachates, particularly if the GCL was not prehydrated prior to contact with the leachate.

Chemical resistance testing should be performed in all instances where a GCL is part of a liner structure. It is not sufficient to rely on product literature, technical literature, or data from other projects. There are too many variations in waste types and leachate to substitute other sources of data for project-specific data.

GCLs are also vulnerable to chemical alteration in final cover systems. There have been some reports of unexpectedly high rates of infiltration into facilities with GCL-based barrier layers without a geomembrane over the GCL. Research has recently been conducted to evaluate the combined effect of desiccation and loss of plasticity that occurs when sodium ions are replaced with calcium ions in the clay component of a GCL. Part of this research simulated the calcium concentrations that might be expected from precipitation percolating through soil in a final cover system. The research indicated that, if a GCL loses plasticity and also undergoes shrinkage cracking, it may not be able to seal up the shrinkage cracks adequately to maintain its original low permeability. In contrast, a GCL that was protected from desiccation still maintained a low permeability even after loss of plasticity due to ion exchange.

This research has been supplemented with a field investigation at a landfill where a GCL was used in a full scale landfill cap, but without a protective geomembrane. Collection basin lysimeters used to monitor the cap showed high infiltration rates, and exhumed GCL panels displayed extensive cracking.

Consequently, GCLs proposed for use in final cover designs should be protected from desiccation cracking effects by an overlying geomembrane. Any final cover design that does not include protection for the GCL should be evaluated by compatibility testing. The permeating fluid used in the test should reflect the ionic composition of water percolating through cover soils. The compressive stress used in the test should not exceed the value expected to result from the weight of final cover soils.

The design of a chemical resistance test should be discussed with department staff prior to conducting the test. However, the general sequence of activities should include the following:

- Characterize the leachate and obtain a supply for use in the testing. A recipe might be developed if the actual leachate contains an organic fraction which is unstable or supports microbial growth in the sample apparatus. The recipe should reflect the highest dissolved inorganic concentrations to be found in the actual leachate, particularly the monovalent and divalent cations and the major anions, as well as pH, electrical conductivity and redox potential (Eh). Drain layer sands and gravels that include minerals with leachable divalent ions (e.g., calcium and magnesium) should also be accounted for in the testing. The constituent ions and concentrations should be reported with any laboratory report.

- Use an accredited testing laboratory with the equipment capable of performing the ASTM D5084 and D5887 test methods. These are tests conducted in a flexible-wall permeameter specifically developed to mount and control GCL samples.

- Organize the testing sequence to test the candidate GCLs with a control using tap water or local groundwater and with a minimum of three replicates with leachate, both with and without prehydration with tap water or local groundwater.

- Run the tests for several pore volumes. Record hydraulic conductivity vs. time, hydraulic conductivity vs. pore volumes, flow rate vs. pore volumes, electrical conductivity ratio vs. pore volumes, and pH ratio vs. pore volumes. The conductivity and pH ratios are the ratio of influent to effluent concentrations. Note that unless these ratios are equal and the chemical composition of the influent and effluent are the same, chemical equilibrium has not been attained and the GCL's properties can be expected to continue to change.

If the GCL proposed for a future phase contains bentonite with significantly different characteristics than the bentonite in the GCL that was originally tested, or if the waste characteristics change over time, the tests should be rerun to reflect the new conditions.

B. Stability

Slopes: Landfills in Wisconsin are restricted to maximum slopes of 3:1 on the liner, and 4:1 on the final cover, for both clay and composite barrier systems. EPA has been monitoring the behavior of several GCL test installations at 2:1 and 3:1 slopes for a few years and has found encouraging short term results with regard to physical stability on the 3:1 slopes. On two of the 2:1 slopes, there were interface friction slides at the geomembrane-GCL interfaces. None of the GCLs experienced internal shear failure. There have been other reports of GCL failures that lack detailed technical descriptions of failure mechanisms.

The physical stability of a proposed GCL on any slope over 10% should be verified by direct shear testing using the GCL, soil barrier, and geomembrane materials to be used in each phase. This means that slope stability testing should be done prior to each phase of site construction. Test results from previous phases might provide supporting data but should not replace actual testing prior to each phase. Specific GCL product details may vary from year to year, with differences in the weight and type of geotextiles used, reinforcement method (by needlepunching or stitching), and source and mineralogy of the bentonite. Their behavior may be different when matched with geomembranes or soil barrier materials from different sources.

ASTM D5321 is the generally accepted direct shear test to be applied to soils and geosynthetics. Each of the soil and geosynthetic contact surfaces should be tested separately. GCLs should also be tested for internal shear strength. Testing should be performed on saturated samples in order to reflect worst case stability conditions. The tests should be run to determine both peak and large-displacement shear strength values.

ASTM D3080 should be used to determine an appropriate direct shear rate. Direct shear tests are often run at a rate of 1 mm per minute. Some researchers have demonstrated that shear rates in this range can produce artificially high shear strength results. Shear rates should be selected to ensure that fully drained conditions prevail in the bentonite, and that the dynamic effects of rapid fiber pullout and tearing do not artificially increase the measured shear strength. Rates of 0.04 mm per minute or less do not seem to adversely influence shear strength determinations.

The amount of overburden pressure used in the test will depend on the application. For final cover systems, the overburden pressure should be no greater than the designed cover soil layers. For liner designs, some feedback from the design and operation is needed. It may be necessary to specify that waste filling be limited to incremental lifts that limit the amount of un-buttressed waste placed against interior sideslopes. This overburden pressure should be applied prior to hydration of the GCL sample.

To ensure that worst case stability conditions are being tested, GCLs should be fully hydrated and other contacts should be tested in a wetted condition. The vertical expansion upon wetting should be verified by monitoring vertical displacement. A good approach is to measure the thickness of the GCL as it hydrates under test normal stress. Complete hydration is indicated when thickness maintains an essentially constant value, e.g., when the rate of change in thickness over a 12-hour period is less than 5 percent.

Moisture samples should be taken from the hydrated GCL after the shear test to confirm the degree of hydration.

Geotextile Options: Geotextile-based GCLs can be manufactured using a variety of needlepunched (nonwoven) geotextiles and woven slit-film geotextiles. Research has shown that the type of geotextile and the style of reinforcement affects internal shear strength, shear strength at interfaces with external surfaces, and degree of direct contact of geomembrane to GCL. For this reason, stability testing should be re-done if the designed interfaces change character as a result of changes in manufacturing methods or materials, or changes in the selected products.

Researchers have observed that, after hydration, enough bentonite can squeeze through the openings in woven geotextiles to create a thin coating on the surface of the weaving. In concept, this coating can lead to better contact with an overlying geomembrane, thus more closely approximating a state of "intimate contact" between geomembrane and clay components, which is a desired condition for a composite liner. Researchers have also found that needlepunched geotextiles allow less squeezeout of bentonite through the geotextile structure and that thicker geotextiles can almost completely prevent squeezeout.

Whether due to less squeezeout or a rougher surface texture, needlepunched geotextiles exhibit better shear resistance against both soils and textured geomembranes (smooth geomembranes are hard enough and smooth enough that neither geotextile style in a GCL provides higher shear resistance).

Designers face a conceptual dilemma in designing sideslopes, since the geotextile style that provides the best contact does not provide the highest shear strength. Some manufacturers and designers have recommended use of a GCL with a woven geotextile on the side facing the geomembrane, to assure the best contact between the two after hydration of the bentonite, and a needlepunched geotextile facing the soil subgrade. However, we recommend using a GCL with needlepunched geotextile on both sides, in conjunction with a textured geomembrane, for increased adhesion to both the soil subgrade and the geomembrane surfaces.

To ensure stability on slopes, non-reinforced GCLs or GCLs using woven geotextiles should be restricted to base grades and sideslopes with slopes of 10% or less. For any slope in excess of 10%, the GCL selected should have needlepunched geotextiles on both sides of the panel.

Quality assurance work should include inspection of GCL placement to assure that the proper side of the GCL is facing upward, for those applications where the geotextile style facing the geomembrane is part of the design.

<u>Settlement</u>: Settlement should not be an issue with respect to GCL use in liners. If a site has a foundation that is likely to settle, the site should be regarded as not feasible, regardless of whether compacted clay or GCL is used in a liner.

With respect to GCL final cover applications, designing for GCL panels to slip during settlement is not good practice. Some designs have called for greater panel overlaps to compensate for settlement (overall or differential). This approach can use up a large part of the panel width, which is generally 15 feet for conventional GCL panels. The problem of settlement should be addressed in the elements below the capping layer, adding, as necessary, high strength geotextile or geogrid reinforcement in the grading or support layers. Neither the GCL nor the geomembrane should be expected to correct for the effects of settlement or to take up the large strains that might develop during such settlement.

C. <u>Soil Barrier Layer</u>

With a few exceptions, it is recommended that GCLs be sandwiched between, and placed in direct contact with, an underlying soil barrier layer and an overlying geomembrane. The three layers or components make up one composite barrier layer.

The geomembrane layer will typically be high density polyethylene in liner systems or a lower density polyethylene in final cover systems. The design standards, testing, and documentation of the geomembrane layer are described in chs. NR 504, 514, and 516, Wis. Adm. Code. The soil barrier layer, however, is not described in regulatory codes and warrants some additional explanation.

The soil barrier layer performs several functions:

- Supporting the GCL, which eliminates the need to bridge gaps in larger aggregate, cracks, and holes. GCLs perform best where they are fully supported.

- Providing support in final cover systems. The action of placing and compacting the soil barrier layer leads to densification of the upper layers of waste. The densified waste and soil barrier layer can protect the GCL and geomembrane from some or all of the effects of settlement.

- Preventing loss of bentonite that might sift or be piped out through the GCL geotextile components.

- Performing as a backup to a geomembrane, in the event that the GCL is defective or deficient in bentonite.

- Providing additional attenuation capacity if the bentonite in the GCL is compromised by chemical attack. The sand, silt, and clay minerals in lower plasticity soils are usually less affected by chemical constituents of leachate than sodium bentonite.

- Controlling loss of landfill gas and influx of air. Incompletely hydrated GCLs are much more permeable to the flow of gas or air than natural soils compacted on the wet side of optimum water content.

- Providing moisture for hydration of the bentonite in GCLs. Research has shown that GCLs reach higher moisture contents when in contact with soils compacted wet of optimum water content.

An effective barrier soil will contain a wide gradation of soil particle sizes with a significant fraction consisting of silts and clays (CETCO recommends a minimum 80% by weight passing the No. 60 sieve, i.e., less than 0.25 mm) and will display good compaction behavior. Recommended Unified Soil Classification System soil types are CH, CL, SM, SC and ML (or dual-symbol classifications composed of these soil types). Where granular soil types (SM or SC) are proposed for use as a soil barrier, they should have a P200 content of greater than 40%, show C_c of greater than 6, and show a C_u between 1 and 3. Sieved soils that preserve a wide gradation and high fines content may also be acceptable. Sands lacking fines, or those containing a large proportion of gravels, and organic soils are not recommended as soil barrier layers.

Research suggests that soil barrier layers should have minimum thicknesses of 12 to 24 inches, depending on the application and waste type, constructed in lifts of no more than 12 inches. Generally, they should be compacted to at least 90 percent of the modified Proctor maximum dry density at moisture contents on the wet side of optimum. Lumps and protrusions should be eliminated on the soil barrier layer by hand-picking and smooth drum rolling. With adequate smooth rolling, a maximum particle size in the barrier layer soil of 1-inch diameter may be acceptable. Ruts greater than 1 inch in depth should be removed.

Soil material placed on top of a GCL (i.e., in the absence of a geomembrane) generally should also be subject to a maximum particle size of 1-inch diameter.

D. Soil Cover

Protection from Freeze-Thaw and Desiccation Damage: The best protection from the effects of freeze-thaw and desiccation is adequate soil cover (this is true for both clay-geomembrane composites and GCL composites). Even though GCLs may have better resistance to the deleterious effects of freeze-thaw or drying and wetting than compacted clay under ideal conditions, they should be protected so as to minimize those effects. A geomembrane would seem to provide protection against desiccation, but research on compacted clay liners covered only with geomembranes has shown that the clay can dry and crack considerably under hot summer conditions. Presumably, GCLs could be similarly damaged. In fact, some field inspections have found that GCL panels shrank so much under a heated geomembrane that panel overlaps pulled apart.

For liners, research indicates the surcharge necessary to hold the geomembrane in contact with the underlying clay or GCL is 2 feet. For covers, the total soil thickness over an installed GCL should be no less than that specified in s. NR 504.07 for final cover systems, i.e., at least 3 feet total, including the drain layer, rooting zone and topsoil. A conservative approach would be to place the GCL--or, for that matter, compacted clay--below the frost penetration depth, which in Wisconsin can be 5 feet or more.

<u>Limiting Free Swell</u>: Because elimination of free swell of bentonite in GCL installations would require some 7 to 8 feet of soil cover, which is impractical in most applications, the goal should be to minimize free swell through proper construction. Current code requirements for compacted clay-geomembrane composites, which call for covering by a drainage blanket or drain layer, rooting zone and topsoil within the same construction season as the liner or capping layer, may inadequately limit free swell. To minimize free swell, composite caps and liners that include GCLs should generally receive cover within a few days of installation, and GCLs without an overlying geomembrane should be covered on the same day they are installed.

<u>Preventing Vehicle Damage</u>: There is a need for GCLs to be covered for protection and to be subjected to some overburden pressure, whether they are used by themselves or with a geomembrane in a composite barrier. The materials to be used to cover a geomembrane/GCL usually have to be hauled and spread by wheeled and tracked equipment, yet the activities of placing the covering soils can lead to damage by rutting or puncture. Damage can be minimized by confining traffic to zones of adequate soil thickness. The minimum cover requirements for traffic on geomembranes in s. NR 504.06(3)(h), Wis. Adm. Code may also be appropriate as guidance for GCLs. An exception may be made for the use of small all-terrain vehicles to deploy the overlying geomembrane.

E. Tie-Ins Between Phases

Landfill liners and final covers are commonly constructed in a phased manner, with cells or phases constructed at intervals that vary from half a year to several years. As a result, the transition area between two phases constitutes an important design element for GCL work.

The following guidelines are offered, although individual site characteristics or design innovations may result in other appropriate designs.

- When a GCL is connected to a compacted clay layer, it should be extended over the edge of the compacted clay at least 3 feet. This may require removal of waste, drainage layer, geomembrane, and confining berms in liner construction, or drain layer, rooting zone, and topsoil in a final cover.

- When two phases containing GCL layers are connected, the edge of the previously constructed phase's GCL should be protected from excess soil moisture contact by plastic construction film rolled over both top and bottom sides for at least a 2-foot width along the edge of the GCL panel, and preferably extending over half of the width of the GCL. The overlying geomembrane should extend beyond the edge of the GCL and also be protected for future uncovering. It is common, for instance, to cover the edge of the geomembrane with ¾ inch plywood panels to provide protection against impact damage when the geomembrane edge is re-exposed. Multiple feet of additional soil should be placed over the edges of the geosynthetics to divert water away from the buried edges and to impose additional overburden pressure to minimize swelling of the GCL. During construction of the subsequent phase, all overburden soil should be removed and the geomembrane pulled back, to allow overlapping the GCL panel edges by at least one foot.

F. GCLs Consisting of Geomembrane and Bentonite

A few GCL products differ from conventional GCLs in that they combine bentonite and a polyethylene geomembrane instead of a geotextile. Because most of the recommendations in this guidance pertain primarily to geotextile-based GCLs, the following considerations should be noted for proposals involving geomembrane-based GCLs.

Some designers have proposed to replace both the clay and geomembrane components of a liner or cover with a geomembrane-based GCL. Geomembrane-based GCL panels are typically proposed to be overlapped, not heat welded. Welding can be difficult if the bentonite that is glued to the geomembrane has to be removed. Since heat welding of geomembrane-based GCLs still appears to be experimental and uncommon, these products should not be regarded as an equivalent replacement for a composite of geotextile-based GCL and geomembrane that is heat welded.

The geomembrane component of a geomembrane-based GCL can be provided in any thickness from 20 mils to 100 mils, but is typically proposed in the 20 to 30 mil range. This limits the unit weight and allows more surface area in a standard roll, but it requires added attention to the overlapped seams and to protection from puncturing, and also increases the potential for damage if welding is attempted.

In current geomembrane-based GCLs, the bentonite is not reinforced and is bound to the geomembrane by water-soluble glue. Without reinforcement, hydrated bentonite may be squeezed by the weight of construction vehicles. Cover soil should be placed soon after the GCL is deployed to minimize such squeezing, and limits on vehicle weights should be at least as stringent as those applied to geotextile-based GCLs.

Since this style of geomembrane is not reinforced and there have been reports of failures on slopes with this material, its use as part of a final cover system or in long interior slopes is not recommended.

Designs proposing use of geomembrane-based GCLs should consider the recommendations in this section but should be justified and supported on their own merits. Any proposal to use a geomembrane-based GCL should clearly address its unique characteristics.

IV. CONSTRUCTION AND DOCUMENTATION GUIDELINES

A. GCL Construction

GCL Storage: GCLs should be stored in a manner that protects them from moisture and exposure to weather. Rolled-up panels should be kept inside sealed plastic wrappers until just before they are to be used. The rolls should be supported off the ground, on pallets or plywood panels along their entire length, and covered by plastic film or sheeting. Proper equipment should be used for support and handling of the rolls, since they can be damaged easily. GCL rolls need support along the entire roll, since buckling can also damage the panel.

Panel placement: GCL panels are handled using methods similar to those used with geomembranes. At the storage area, the plastic wrapping is removed immediately before an individual roll is deployed. The transport and lifting machine is generally an endloader. A spreader bar is suspended from the machine bucket or arm and inserted through the hollow cardboard core of the GCL roll. Picking up a GCL roll by forklift arms or other means is likely to damage the GCL.

The endloader deploying the GCL either remains stationary and supports the roll while it is pulled out, or backs up from the anchor trench and unrolls the panel. During deployment of the panel by the endloader, rutting of the subgrade may occur, reducing the effectiveness of the composite liner system.

On any slope greater than 10%, panels should be oriented parallel to the slope (i.e., running down the slope), and run out beyond the toe of slope 5 to 10 feet. End seams on slopes should be avoided or minimized. Where an end seam is necessary, it should utilize a 20-inch overlap, with the overlap shingled downslope, and should have no end seams within 25 feet up- or downslope on adjacent panels.

Anchor trenches are generally used at the top of slopes for securing geomembranes, geotextiles, and GCLs during liner construction. Generally, the GCL and geomembrane can be anchored in a common anchor trench. Once a site has been constructed and filled, the stability of geosynthetics on interior sideslopes is based on the frictional resistance on the slope, not on the tensile reinforcement afforded by anchorage at the top of the slope. During construction and prior to filling, however, tensile reinforcement may play a part in GCL stability on slopes.

For protection against physical damage and premature hydration, GCL panels should be covered by a geomembrane (in composite barrier structures) on the same day the GCL is laid down, and by a soil layer as soon thereafter as possible, but in any case within the next few days. GCL panels should be laid down in a relaxed condition, free of wrinkles and without stretching the panel.

The GCL should be checked to ensure that the proper side is facing up according to the designer's specifications. Many brands of GCLs are manufactured with indicator markings for the proper side up imprinted on the geotextile.

GCL panels should be deployed in order to achieve the proper amount of overlap without contaminating the overlap area with underlying soil. The overlap area needs to be clean to ensure a tight seal along seams. If the deployment sequence requires that the overlap be switched after deployment, the upper panel should be folded back and the lower panel gently shaken or brushed to remove soil lodged on the bottom of the lower geotextile prior to the overlap being switched.

<u>Geomembrane placement</u>: GCL and geomembrane installation should occur at the same time. In practice, the same crews usually install both geosynthetic materials. While placement of GCL panels is relatively straightforward, placing geomembrane panels over GCL panels requires some specialized methods and will slow the overall geosynthetic installation process. The basic problem is that large construction equipment typically used to unroll geomembranes cannot be allowed to run over the GCL. The weight of the equipment can damage the GCL by laterally displacing the bentonite or by deforming the subgrade under the wheels. In fact, no large equipment, whether wheeled or tracked, should travel over either GCL or geomembrane surfaces without an adequate cushion of soil.

On shallower slopes and with smooth geomembrane, the geomembrane can be deployed over the GCL by laborers or small four-wheel-drive all-terrain vehicles (ATVs). Pulling the smooth geomembrane over the GCL is relatively easy but it does result in bentonite dust coating the geomembrane, including the edges that have to be heat seamed. Deploying the geomembrane off to the side of the GCL panels is an alternative, but still results in the geomembrane having to be pulled into place. At this point, there is not enough industry feedback to say if one method is clearly superior to the other.

On steeper slopes, where textured geomembranes are typically used, a "rub sheet" or slip sheet made of thin plastic film is usually placed over the GCL before pulling the geomembrane over it. The geotextiles in the GCL adhere so well to the texturing that textured geomembranes cannot be pulled over the GCL without damaging one or the other. Pulling the geomembrane out over the plastic film using laborers or ATVs can become impractical due to the slippery footing and weight of the panel. One alternative method that has shown success on slopes is the use of a tracked backhoe with sufficient reach to suspend the geomembrane roll over the GCL while traveling on the subgrade parallel to the edge of the GCL. Once the geomembrane panel is positioned for correct overlap and welded to the panel next to it, the slip sheet can be pulled (with some considerable tugging by the laborers) out from between the GCL and geomembrane panels, folded back over the geomembrane, and be in position for pulling over the next GCL panel to be laid out.

Department staff have observed a GCL installation where a textured geomembrane was pulled over the GCL by an ATV. Fibers in the upper geotextile of the GCL were visibly pulled and torn. Of more concern is that the geotextile fabric was degraded or “combed out” along the alignment of the panel. This type of degradation may have two effects. The geotextile fibers in direct contact with the geomembrane are weakened or broken, and potential shear resistance between the textured geomembrane and the upper geotextile of the GCL is reduced. Abrasion between the geotextile and geomembrane may also smooth down some of the texturing of the geomembrane, leading to further compromise of the shear resistance between the two materials. Consequently, it is recommended that textured geomembrane be unrolled and maneuvered over a slip sheet rather than directly on the upper surface of a GCL panel.

<u>Seaming</u>: GCL panels are not physically bonded to each other. Seaming is accomplished by simply overlapping adjacent panels and may or may not include a layer of loose bentonite at the overlap. Current industry recommendations for overlaps are 6 inches for lateral seams (parallel to the roll edges), 20 inches for end seams (end of roll edges), and 6 to 12 inches for patches and angle cuts. Most GCL products are preprinted with overlap markings along their long edges.

Panel laydown should be organized to avoid end seams on slopes. Since GCLs are manufactured in lengths of about 150 feet, larger sites that contain longer slopes will necessarily involve end seams on slopes. In such cases, seams should be staggered to avoid being close to each other.

Generally, additional granular bentonite is placed between the overlap along seams for needlepunched GCLs. The industry-recommended rate is one quarter pound of bentonite per foot of seam. It is good practice to use an application machine rather than estimating hand applications. The application rates should be checked periodically to verify machine settings or crew practices. Generally, industry recommendations do not call for granular bentonite in the seam overlaps for glued GCLs with thin woven geotextile backing.

More loose bentonite is not better. A mass of loose bentonite below the geomembrane can act as a slippage zone. Also, loose bentonite can generate dust that gets into geomembrane overlaps, compromising fusion and extrusion weld quality. It is probably impossible to totally prevent dust in the seams, but the problem can be minimized by good welding practices. Extrusion welding includes an abrasion step that effectively removes bentonite dust. Fusion welded seams should be cleaned before being welded. Cleaning with dry cloth or paper towels is recommended. Wet towels may hydrate the bentonite and make it even more difficult to remove.

Patches and penetrations: Techniques for creating patches and connections to penetrations (such as gas wells penetrating a final cover) are not yet fully developed. Much depends on the designer's or installer’s creativity. The general pattern is to cut a hole or a pair of perpendicular slits in the panel close to or just smaller than the diameter of the penetration, and fold or pull the panel over the penetration. To provide support around the penetration and under the GCL and geomembrane, all voids should be filled in and packed with a mixture of sand and 10% to 25% powdered bentonite, mixed and placed dry. Any voids or gaps below the geosynthetics can lead to bridging, stretching, tearing or slipping, and ultimate failure.

Premature hydration: It should never be necessary to intentionally hydrate GCLs in landfill construction. GCL panels should absorb sufficient moisture from the soil subgrade.

Excessive wetting of GCL panels prior to covering can lead to unconfined swelling of the bentonite. Some consulting engineers and GCL suppliers have reported cases in which large exposed areas of GCL panels have been soaked by unexpected heavy rains. The rapid expansion of the bentonite creates a soft and sticky surface, and, especially with nonreinforced, glued GCL panels, may lead to squeezeout of bentonite due to foot or vehicle traffic, or, in the case of unreinforced GCL panels, masses of bentonite flowing downslope. Light, short rains appear to be less of a problem, especially for reinforced GCLs, in which the heavier geotextiles more effectively protect the bentonite from wetting.

Excess wetting is evidenced by the presence of hydrated bentonite on or in the GCL, a significant increase in the weight of panels, or an increase in panel thickness.

Excessively wetted GCL panels are impractical to cover with geomembrane or soil and must be cut away and removed. The removal process itself is difficult, since the GCL panels are not only wet and slippery but weigh considerably more than they did initially.

Excessively wetted GCL panels cannot be practically dried out and reused. Without the compression of overburden pressure, the bentonite expands so much that, upon drying, cracks form which are too large to bridge reliably when the GCL rehydrates.

Any decisions about whether GCL panels have to be replaced should be based on the judgment of the onsite quality assurance personnel, not the installer.

During construction of composite liners or capping layers, only enough GCL panels are laid out to allow placement and welding of geomembrane panels over the GCL panels during the same day. At the end of the day, any exposed GCL panel edges should be covered by overlying geomembrane or the exposed GCL panel edges should be covered by additional geomembrane or plastic sheeting. The edges of the geomembrane or sheeting may have to be shingled or weighted down sufficiently to prevent any overnight precipitation from running under the sheeting and contacting the GCL edges.

In all instances where a GCL/geomembrane composite is used, the cover soil components should be placed over the GCL/geomembrane composite within a few days of installation so that the confining pressure can limit the amount of free swell of bentonite that occurs. The higher the moisture content of the subbase layer below the GCL, the sooner the soil cover should be placed. Where a GCL is used without an overlying geomembrane, the cover soil components should be placed over the GCL on the same day the GCL is installed.

Some landfills have been allowed to build composite-lined sideslopes and then place the leachate collection layer incrementally. This is poor practice since desiccation of the underlying liner can occur. Also, a GCL requires some overburden weight to prevent excessive swelling by moisture absorption from the soil subgrade.

B. Reports

Preconstruction report: A preconstruction report should be submitted for Department review prior to the beginning of construction. This report should present information about the manufacturer and installer of the GCL, the GCL product itself, and the quality assurance contractor and QA plan. It should describe the methods and equipment to be used in installing the GCL and associated liner/cover components, and provide a planned panel layout diagram. If the GCL is to be placed in contact with a geomembrane, the GCL product should be certified by its manufacturer to be free of broken-off needles from the needlepunching process. The preconstruction report should also present results from compatibility and physical stability testing.

Construction documentation report: General contents include:

- Identification of GCL manufacturer, GCL product and properties, and samples of manufactured materials used
- Manufacturing quality assurance methods and data
- Details of wrapping, shipping, and storage on site
- Conformance testing results
- Equipment and methods used to handle GCL rolls during installation
- Condition of subgrade (absence of ruts, gravel, etc.) and corrective measures taken
- Field records of panel installation, repairs, covering and replacement
- Detailed discussion, drawings and photographs of penetrations and tie-in areas
- QA logs
- Construction documentation testing and observations of installation quality

- Photographs of the installation process

It is recommended that samples of various GCL rolls used in site construction be archived, similar to geomembrane destructive samples. Archived samples should be sealed in plastic bags and retained for a minimum of 5 years and should be discarded only after consultation with department staff.

V. REFERENCES

Copies of the following materials, as well as additional relevant references, have been compiled by the authors and are located in GEF 2, WA/3, Technical Support Section.

Refereed Technical Journal Articles

Boardman, B. Tom and Daniel, David E. (1996), “Hydraulic Conductivity of Desiccated Geosynthetic Clay Liners”, J. Geotech. Eng., ASCE, Vol. 122, No. 3, March, 204-208.

Daniel, David E., Koerner, Robert M., Bonaparte, Rudolph, Landreth, Robert E., Carson, David A., and Scranton, Heather B. (1998), "Slope Stability of Geosynthetic Clay Liner Test Plots", J. Geotech. and Geoenv. Eng., ASCE, Vol. 124, No. 7, July, 628-637.

Eid, H.T. and Stark, T.D. (1997), “Shear Behavior of an Unreinforced Geosynthetic Clay Liner”, Geosynthetics International, Vol. 4, No. 6, 645-659.

Estornell, Paula and Daniel, David E. (1992), “Hydraulic Conductivity of Three Geosynthetic Clay Liners”, J. Geotech. Eng., ASCE, Vol. 118, No. 10, October, 1592-1606.

Gilbert, Robert B., Fernandez, Federico, and Horsfield, David W. (1996), “Shear Strength of Reinforced Geosynthetic Clay Liner”, J. Geotech. Eng., ASCE, Vol. 122, No. 4, April, 259-266.

Hewitt, Robert D. and Daniel, David E. (1997), “Hydraulic Conductivity of Geosynthetic Clay Liners After Freeze-Thaw”, J. Geotech. and Geoenv. Eng., ASCE, Vol. 123, No. 4, April, 305-313.

James, Anthony Noel, Fullerton, David, and Drake, Ramon (1997), “Field Performance of GCL Under Ion Exchange Conditions”, J. Geotech. and Geoenv. Eng., ASCE, Vol. 123, No. 10, October, 897-901.

Kraus, Jason F., Benson, Craig H., Erickson, Allan E., and Chamberlain, Edwin J. (1997), “Freeze-Thaw Cycling and Hydraulic Conductivity of Bentonitic Barriers”, J. Geotech. and Geoenv. Eng., ASCE, Vol. 123, No. 3, March, 229-238.

LaGatta, Mark D., Boardman, B. Tom, Cooley, Bradford H., and Daniel, David E. (1997), "Geosynthetic Clay Liners Subjected to Differential Settlement", J. Geotech. and Geoenv. Eng., ASCE, Vol. 123, No. 5, 402-410.

Lin, Ling-Chu and Benson, Craig H. (2000), "Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of Geosynthetic Clay Liners", J. Geotech. and Geoenv. Eng., ASCE, Vol. 126, No. 1, 40-49.

Ruhl, Janice L. and Daniel, David E. (1997), "Geosynthetic Clay Liners Permeated with Chemical Solutions and Leachates", J. Geotech. and Geoenv. Eng., ASCE, Vol. 123, No. 4, 369-381.

Stark, T.D. and Eid, H.T. (1996), "Shear Behavior of Reinforced Geosynthetic Clay Liners", Geosynthetics International, Vol. 3, No. 6, 771-786.

Trade Journal Articles

Daniel, David E. and Richardson, Gregory N. (1995), "A Position Paper on: The Role of Geomembranes and Geosynthetic Clay Liners in Landfill Covers", Geotechnical Fabrics Report, Vol. 13, No. 1, Jan.-Feb., 44-49.

Egloffstein, Thomas (1997), "Geosynthetic Clay Liners, Part Six: Ion Exchange", Geotechnical Fabrics Report, Vol. 15, No.5, 38-43.

Koerner, Robert M. and Daniel, David E. (1992), "Better Cover-Ups", Civil Engineering, May, 55-57.

Mackey, Robert E. (1997), "Geosynthetic Clay Liners, Part Five: Design, Permitting and Installation Concerns", Geotechnical Fabrics Report, Vol. 15, No. 1, Jan.-Feb., 34-39.

Richardson, Gregory N. (1997), "GCLs: Alternative Subtitle D Liner Systems", Geotechnical Fabrics Report, Vol. 15, No. 4, 36-42.

Richardson, Gregory N. (1997), "GCL Internal Shear Strength Requirements", Geotechnical Fabrics Report, Vol. 15, No. 2, March, 20-25.

Conference Proceedings & Technical Papers

Cooley, B.H. and Daniel, D.E. (1995), "Seam Performance of Overlapped Geosynthetic Clay Liners", Proceedings of Geosynthetics '95, IFAI, February 21-23, 1995, Nashville, TN, 691-705.

Corser, P. and Cranston, M. (1991), "Observations on Long-Term Performance of Composite Clay Liners and Covers", Proceedings, Geosynthetic Design and Performance, Vancouver Geotechnical Society, May 24, 1991, Vancouver, B.C., 16 pp.

Daniel, David E., (1993), "Geosynthetic Clay Liners (GCLs) in Landfill Covers", presented at the Thirty-First Annual Solid Waste Exposition, SWANA, San Jose, CA, Aug. 2-5, 1993, 29 p.

Daniel, David E., Shan, H.-Y., and Anderson, J.D. (1993), "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner", Proceedings of Geosynthetics '93, IFAI, March 30-April1, 1993, Vancouver, BC, 1483-1496.

Evans, W. Douglas, Stark, Timothy D., Wilson, Virginia L., and Gonda, Joseph M. (1998), "Design Considerations for Geosynthetic Clay Liners", Proceedings of the 20th International Madison Waste Conference, Department of Engineering and Professional Development, Univ. of Wisconsin, April 1-2, 1998, Madison, WI, 203-218.

Harpur, W.A., Wilson-Fahmy, R.F., and Koerner, R.M. (1993), "Evaluation of the Contact Between Geosynthetic Clay Liners and Geomembranes in Terms of Transmissivity", Proceedings of the 7th GRI Seminar, Geosynthetic Research Institute, Drexel University, Philadelphia, PA, 138-149.

Koerner, R. and Daniel, D (1994), "Assessing the Technical Equivalency of GCLs to CCLs", Proceedings of the 7th GRI Seminar: Innovations, Concerns, and Designs, December 14-15, 1993, Geosynthetic Research Institute, Drexel University, Philadelphia, PA, pp. 255-275.

Melchior, Stefan (1997), "In-Situ Studies on the Performance of Landfill Caps", Proceedings of the 1997 International Containment Technology Conference, February 9-12, 1997, St. Petersburg, FL, 9 pp.

Shan, Hsin-Yu and Daniel, David E. (1991), "Results of Laboratory Tests on a Geotextile/Bentonite Liner Material", Proceedings of Geosynthetics '91, IFAI, February 26-28, 1991, Altanta, GA, 517-535.

Trauger, R.J. and Lucas, H.L. (1995), “Determining the Flow Rate of Landfill Gas Constituents Through a Geosynthetic Clay Liner”, Proceedings of Geosynthetics ‘95, IFAI, February 21-23, 1995, Nashville, TN, 1085-1096.

Wilson-Fahmy, R.F. and Koerner, R.M. (1995), “Leakage Rates Through Holes in Geomembranes Overlying Geosynthetic Clay Liners”, Proceedings of Geosynthetics ‘95, IFAI, February 21-23, 1995, Nashville, TN, 655-668.

Training Session Notes

Short Course Notes for “Geosynthetic Clay Liners for Waste Containment and Pollution Control”, held June 10-12, 1996, at University of Texas, Austin, TX. Sponsored by the Civil Engineering Department and instructed by Prof. David Daniel, Prof. Robert Gilbert, and Dr. John Bowders.

Short Course Notes for “Geosynthetic Clay Liners (GCLs) for Waste Containment”, held October 23-24, 1997, in Rosemont, IL. Sponsored by Dept. of Civil Engineering, University of Illinois at Urbana-Champaign and instructed by Prof. David Daniel.

Government and Other Publications

Bonaparte, R., Othman, M.A., Rad, N.R., Swan, R.H., and Vander Linde, D.L. (1996), “Evaluation of Various Aspects of GCL Performance”, Appendix F from “Report on 1995 Geosynthetic Clay Liner Workshop”, USEPA, 1996, 34 pages.

Daniel, D.E. and Boardman, B.T. (1993), “Report of Workshop on Geosynthetic Clay Liners”, USEPA, Cincinnati, OH, EPA/600/R-93/171, 106 pp.

Daniel, David E. and Koerner, Robert M. (1993), ”Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities”, USEPA, Cincinnati, OH, EPA/600/R-93/192, 305 pages.

Daniel, D.E. and Scranton, H.B.(1996), “Report on 1995 Geosynthetic Clay Liner Workshop”, USEPA, Cincinnati, OH, EPA/500/R-96/149, 96 pages plus 8 appendices.

Evans, Doug (1997), "Advisory on Structural Integrity Considerations for Incorporating Geosynthetic Clay Liners in Solid Waste Landfill Facility Design", Ohio Environmental Protection Agency, Division of Solid and Infectious Waste Management Memorandum, Columbus, OH, September 17, 1997, 12 pages.

Koerner, Robert M. (1994), "Designing with Geosynthetics", Third Edition, Prentice-Hall, Englewood Cliffs, NJ, 783 pages. (Chap. 6, "Geosynthetic Clay Liners")

USEPA (1997), "Geosynthetic Clay Liners Used in Municipal Solid Waste Landfills", EPA530-F-97-002, July, 8 pages.

Well, L.W., ed., (1997), "Testing and Acceptance Criteria for Geosynthetic Clay Liners", STP 1308, American Society for Testing and Materials, Philadelphia, PA, 269 p.

Industry Trade Literature

Colloid Environmental Technologies Co. (CETCO), product literature binders - with cover letters dated April 1996 and June 1997 (Claymax and Bentomat products)

Fluid Systems (FSI), product literature binder - with cover letter dated August 1997 (Bentofix products)